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THE TRACE FOSSIL RECORD FROM THE GUARÁ FORMATION (UPPER JURASSIC?), SOUTHERN BRAZIL [1]

(With 15 figures)

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ABSTRACT: In the southwest region of Rio Grande do Sul State, the eolian facies of the Guará Formation (Late Jurassic?) reveals footprints and trackways of vertebrates, as well as burrows made by invertebrates and vertebrates. The footprints are not well preserved and can be distinguished only by the deformation of the sandstone laminations. Some eolian sand sheet layers are totally disturbed by superimposed trackways. Rounded footprints, with diameters about 50cm, can be seen in these sand sheets facies, isolated or forming trackways, and can be observed both on surfaces and in section. The size and shape of the footprints lead us to attribute them to middle-sized sauropods. Inside some of these tracks, little vertical burrows that terminate in basal horizontal chambers are attributed to insects. Three-fingered footprints – isolated or forming trackways –, can also be seen both in section and on surfaces, in sand sheet layers or cutting the foresets of paleodunes. Footprints occur in different sizes (the longest reaching about 45cm in length) and shapes. Although their outlines are often not well-defined, it is possible identify some characteristic patterns pointing to bipedal ornithopods and theropods. In a paleodune, associated with footprints, elongate horizontal partially filled burrows about 20cm wide are tentatively attributed to burrowing mammals. Association of sauropods, ornithopods, and theropods is common from Triassic to Cretaceous periods, and does not support a precise age establishment for the Guará Formation. Nevertheless, it is compatible with the Late Jurassic age attributed to the basal member of the Tacuarembó Formation from Uruguay (lithostratigraphically coeval to the Guará Formation).

Key words: Ichnofossils. Jurassic/Cretaceous. Paraná Basin. Stratigraphy.

RESUMO: Registro de traços fósseis da Formação Guará (Jurássico Superior?), sul do Brasil.

Na região sudoeste do estado do Rio Grande do Sul, nas fácies eólicas da Formação Guará (Jurássico Superior?), foram encontradas pegadas e trilhas de vertebrados, bem como escavações feitas por invertebrados e vertebrados. As pegadas não estão bem preservadas e podem ser distingüidas somente pela deformação do sedimento. Algumas camadas de lençóis de areia eólicos estão completamente bioturbadas por pegadas superpostas. Pegadas arredondadas com cerca de 50cm de diâmetros podem ser encontradas nesses lençóis de areia eólicos, isoladas ou em trilhas, e podem ser observadas tanto em planta quanto em perfil. O tamanho e a forma das pegadas permitem classificá-las como saurópodes de médio porte. Dentro de algumas pegadas foram encontradas pequenas escavações terminadas em câmaras atribuídas a insetos. Pegadas tridátilas – isoladas ou formando trilhas –, podem também ser vistas em planta e em perfil, nos lençóis de areia eólicos ou cortando o *foreset* de uma paleoduna. Nestes foram encontradas pegadas de diferentes tamanhos (a maior com 45cm de comprimento) e formas. Os contornos, em alguns casos, não são bem definidos dificultando a identificação mais precisa. Entretanto, foi possível reconhecer alguns padrões que apontam para ornitópodes e terópodes bípedes. Associado a pegadas em uma paleoduna, tocas preenchidas e horizontais com diâmetros ao redor de 20cm são tentativamente atribuídas a mamíferos. A associação de saurópodes, ornitópodes e terópodes não possibilita uma datação precisa, mas é compatível com a idade Jurássico Superior atribuída à Formação Tacuarembó, unidade correlata do Uruguai, embora nenhum táxon comum tenha sido encontrado, até o momento, para as duas unidades.

Palavras-chave: Icnofósseis. Jurássico/Cretáceo. Bacia do Paraná. Estratigrafia.

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INTRODUCTION

The Guará Formation has a wide geographical distribution (Fig.1), cropping out in the southwestern portion of the Rio Grande do Sul State. Its northwestern limit is controlled by a NW-trending fault system. Lithologically, it is composed of fine to coarse-grained sandstone, and rare mudstones, deposited by fluvial and eolian depositional systems (Scherer *et al.*, 2000). Although highly variable, it has a medium thickness of 200m and rests unconformably over the fluvial deposits of the Lower Triassic Sanga do Cabral Formation. Above, the Guará formation is unconformably overlaid by the eolian deposits of the Lower Cretaceous Botucatu Formation (Scherer *et al.*, 2000).

The Guará Formation is characterized by marked facies variation along the outcropping sequence. The SW portion is characterized by the alternation of eolian and fluvial sediments while the NW one is dominated by fluvial layers. These last show an erosive basal surface and are composed of sandstones with granules, moderately-sorted, with trough cross-bedding and low-angle cross lamination. The eolian sediments are characterized by the presence of fine to medium sandstones, well-sorted, presenting large cross-bedding composed of grain flow, grain fall, and wind-ripple laminations, interpreted as eolian dune deposits, or horizontal wind-ripple strata, interpreted to represent eolian sand sheet deposits.

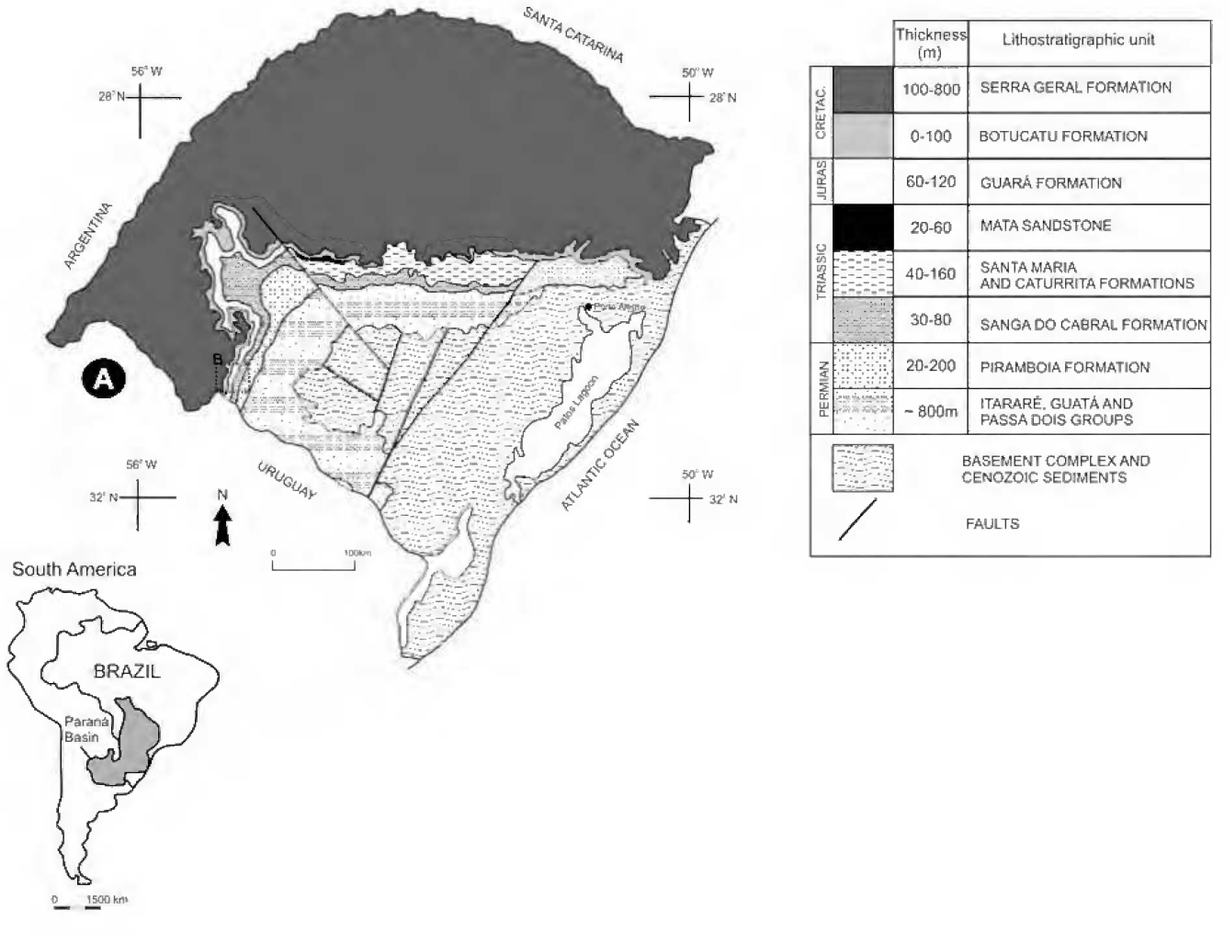


Fig.1- Geological map of the Permian and Mesozoic lithostratigraphic units of the Paraná Basin in the Rio Grande do Sul State, Brazil (After Scherer & Lavina, 2005).

The Guará Formation extends from the Southwest of Rio Grande do Sul State to the Uruguay territory, where it corresponds, lithostratigraphically, to the basal member of the Tacuarembó Formation (Lavina *et al.,* 1985), which yields a rich and diversified fossil record, including a crocodile, semionotiform fish, gastropods and conchostracans (Mones & Figueira, 1980; Ferrando *et al.*, 1987). Nevertheless, no common taxon was found until now for both the Tacuarembó and Guará formations.

In the Guará Formation, near Santana do Livramento and Rosário do Sul cities, where the eolian facies outcrop, footprints and trackways, attributed to sauropod, theropod, and ornithopod dinosaurs, occur. In all the cases, the sediments that cover the footprints are the same as those in which the footprints were produced (*i.e.*, sand), so that no lithological discontinuities occur between the footprints and the infilling sediment. Due to this fact, the footprints can be identified only by the deformation of the sandstone laminations. They often have no relief, and only their outlines can be distinguished, both in surface view and in section. So, anatomical details, such as marks of digits or claws, are very difficult to distinguish. In addition to the footprints, different kinds of burrows, some attributed to little vertebrates and others to invertebrates, were also found at the eolian facies (Schultz *et al.*, 2002; Dias *et al.*, 2002; Dias & Schultz, 2003; Dentzien-Dias & Bertoni-Machado, 2005).

Some of these ichnofossils (including footprints, trackways, and burrows), originating from five different outcrops, are described in this paper.

The Guará Formation also contains, subordinate to the eolian facies, various fluvial layers, that outcrop between Rosário do Sul and Santana do Livramento cities.

If a Late Jurassic age is confirmed for the Guará Formation, the occurrence of these footprints and burrows in the SW of Rio Grande do Sul State would represent a unique record of tetrapod fossils from that age to Brazil.

MATERIAL AND METHODS

A stratigraphic section was made at each fossiliferous outcrop, in which the layers with ichnofossils were marked. The sedimentary facies were described following the model of Reading (1986). The small thicknesses of the stratigraphic sections results from the fact that the outcrops are sparse and not continuous.

The footprints were catalogued following the methodology of Leonardi *et al.* (1987): all the footprints are represented by four letters; the first two refer to the municipal district and the last two to the locality, obtained from topographic maps (scale 1:50000). The codes and the numbers follow the order in which the footprints were discovered.

Following these rules we have:

SLCP = Santana do Livramento – Cerro Palomas (*Chart of Palomas* - 2992/3)
RSSJ = Rosário do Sul – Sanga do Jacaré (*Chart of Saicã* - 2979/2)
RSCT = Rosário do Sul – Cerro Torneado (*Chart of Saicã* - 2979/2)
RSGV = Rosário do Sul – Granja Santa Vitória (*Chart of Saicã* - 2979/2)
RSTP = Rosário do Sul – Touro Passo Stream (*Chart of Saicã* - 2979/2)

All the ichnological material was photographed and measured. The parameters of the footprints, such as length, width and variation of digits, as well data regarding the trackways (width of pace, step angle, length of stride and oblique pace), also follow the model of Leonardi *et al.* (1987).

In outcrop RSCT it was possible to collect two separate footprints. In the RSSJ outcrop one pair was collected. They were registered in the Laboratory of Palaeovertebrates of the Universidade Federal do Rio Grande do Sul (UFRGS PV 0003 J/K , UFRGS PV 0004 J/K and UFRGS PV 0005 J/K).

RESULTS

DESCRIPTION OF FOSSILIFEROUS OUTCROPS

The first outcrop bearing dinosaur trackways is located in the KM 549 of BR-158 road (SLCP). It is represented by the section shown in figure 2. From the base to the top there is a succession of eolian dunes, eolian sand sheets, lacustrine layers and a new succession of dunes at the top. The footprints occur only in the eolian layers, whose palaeocurrents are always directed to E. The SLCP footprints occur at three different levels inside the eolian sand sheet layer.

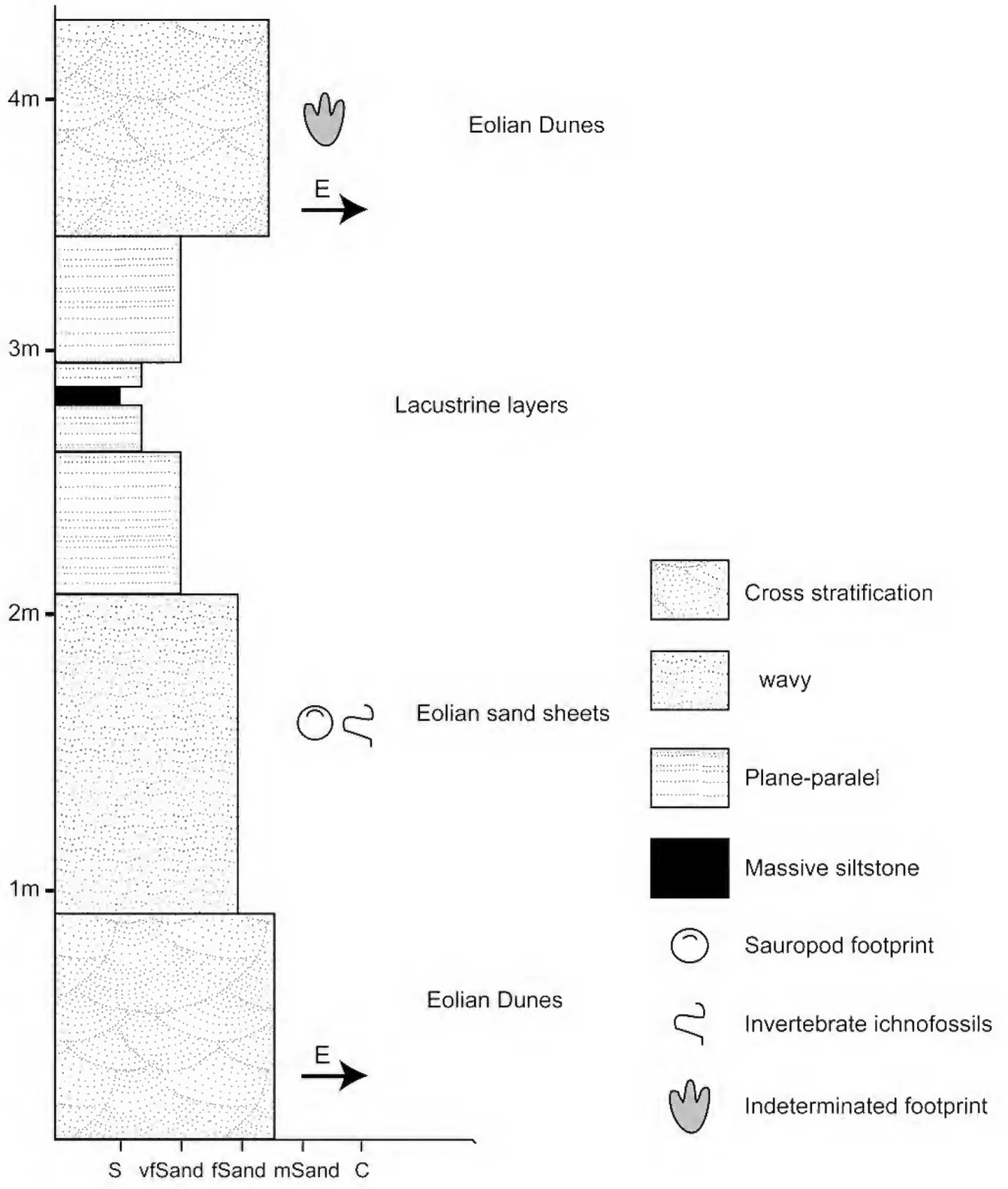


Fig.2- Stratigraphic section of the SLCP outcrop.

On the surface of the outcrop it is revealed trackways and isolated footprints on the surface and in section. The footprints are all rounded (Fig.3), without traces of digits, and two almost parallel trackways can be observed, as well as some isolated footprints. The medium diameter of the footprints is about 50cm. One of the isolated footprints shows deformational features that suggest that the animal was moving from NW to SE.

The trackways were made by a quadruped in spite of there is no manus track. This conclusion is based on the "trackway configuration" (step, stride, and pace angulation). Probably this pattern is due to the poor preservation of the footprints and/or to the overlap of the *pes* overstepping the *manus* footprints, a common phenomenon in sauropod trackways (Moreno & Benton, 2005). We believe, from the evidence of pace angulation patterns and footprint shape (Faria dos Santos *et al.*, 1992), that it is better to attribute them to the pes of a sauropod. The morphology and the size of the footprints suggest the presence of a sauropod with a body size similar to an extant elephant. Nevertheless, these proportions could be also compatible with those of a big prosauropod (like *Riojasaurus* from Argentina, for example). This observation is important because the age of the Guará Formation is not yet surely established. Its basal layers overlay the Early Triassic Sanga do Cabral Formation, so that the presence of rounded footprints in the Guará Formation, by itself, should not exclude an age older than Jurassic for that unit given that such footprints are known from the Triassic.

Inside most footprints, several little vertical burrows can be observed. One of them was excavated to allow its observation in section. These small burrows begin as vertical tubes which become horizontally enlarged at their bases, forming little chambers (Fig.4). These morphological features lead us to attribute these burrows to insects (Renata Guimarães Netto, pers.com).

Other two layers with trackways can be seen in the SLCP outcrop, but only in section, at the wall of the roadcut. The upper one shows only some shallow and not well-defined deformations in the stratification, which do not furnish reliable information. Near the base of the roadcut wall a bigger and very clear trackway is present (Fig.5).

Fig.3- Sauropod footprints on the surface from the outcrop SLCP. The trackways were highlighted by white (south trackway) and black (north trackway) circles, while the grey ones represent isolated footprints; fig.4- Sauropod footprint in surface view and in section (outcrop SLCP). In detail, an ichnofossil made by an insect.

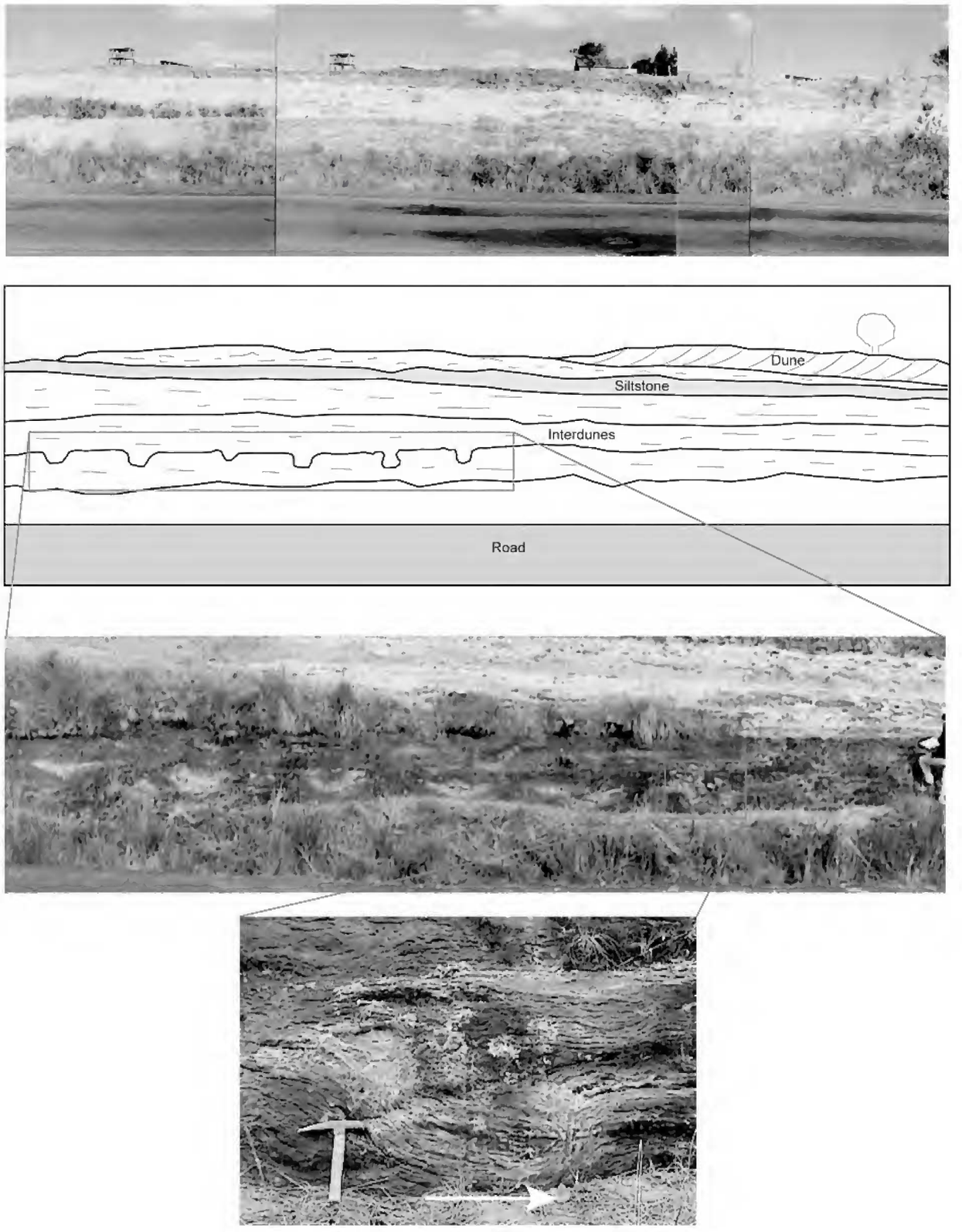


Fig.5- Outcrop in section with a sauropod trackway. The arrow shows that the animal was moving to west.

The footprints are about 50cm wide and the undertracks reach around 45cm in depth. The deformation of the stratification inside the footprints is clearly asymmetric. A deeper portion is always present at the right side of each footprint, which resulted from the pressure created by the anterior portion of the foot during the step. This spatial orientation indicates that the animal was moving from East to West (left to right in figure 5). The direction of the wall is slightly different from that of the trackway, so that the footprints gradually come out from the wall. Indeed, the last footprint of the trackway (SLCP 07) can be partially seen in section, showing its rounded shape (Fig.6). The absence of additional footprints in the western portion of the outcrop leads us to conclude that this trackway represents successive steps of the left foot of the animal. Regarding the trackways that occur on the surface of the outcrop, probably the footprints were produced by the pes overlapping those of the *manus*. The distance between successive footprints in this trackway (length of pace) is 1.20m, while in the surface trackways the lengths of the paces are 1.3m (for the right trackway = North, Fig.7) and 1.4m for the other (Fig.8).

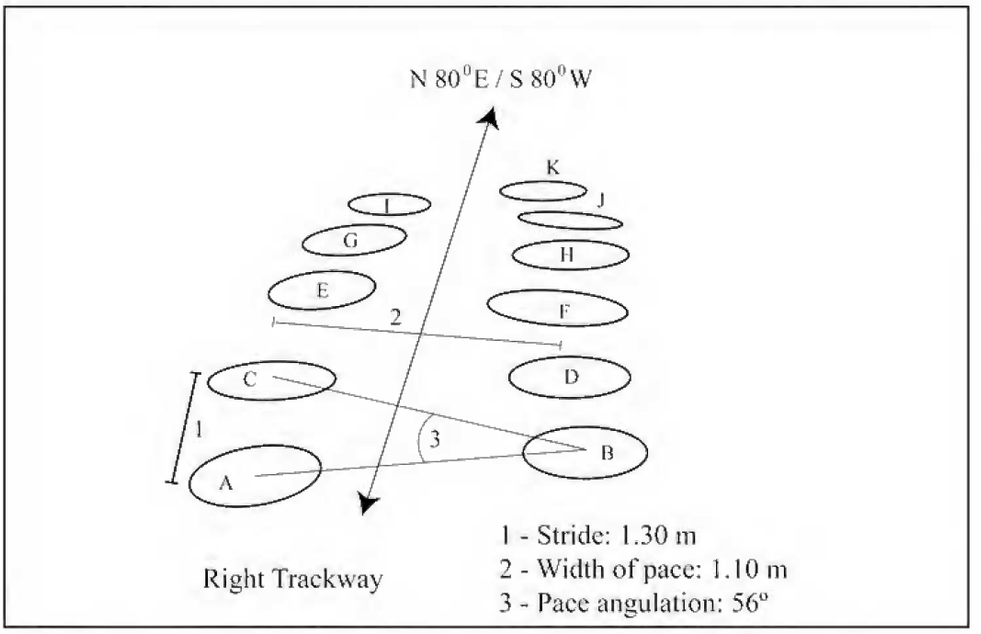
In the upper portion of the outcrop, represented by eolian dunes, another footprint can be seen in section. But it is too poorly preserved to permit a classification.

The second fossiliferous outcrop found in the Guará Formation (RSSJ) is situated in a dirt road west of the town of Rosário do Sul, near the Sanga do Jacaré creek. This outcrop is composed only of paleodunes, whose palaeocurrents are directed eastward. A trackway composed of two three-toed theropod footprints can be observed – in surface view and in section (Fig.9) –, oriented up the foresets of one of the dunes. In section, slide structures formed during this climbing can be clearly seen. These footprints were initially visible only in section, but an excavation was made to expose them in plan. It revealed that these footprints are tridactyl, with marks of sharp claws at their ends. They measure about 17cm in length. This morphology indicates that these footprints were made by a theropod and the size of the footprints suggests that it was no bigger than an extant ostrich.

In the upper level of this same outcrop several ribbons of massive sandstone can be observed crossing the sets of a palaeodune (Fig.10). These ribbons are lens-shaped in transverse section and have a regular width of about 20cm. The thickness of the ribbons range between 3 and 10cm and their lengths vary from 0.40m to 2.80m. These structures tend to be rectilinear, but some of them describe curves and at least one of them reveals a bifurcation (Fig.11). In some portions, these ribbons are covered by little blocks of stratified sandstones. The ribbons of massive sandstones are here interpreted as the floor of burrows, while the stratified blocks evidently represent the collapse of parts of the roof inside the burrows. The size and shape of these burrows is compatible with excavations done by small reptiles or mammals (Miller *et al.*, 2001), as can be illustrated by the extant *Ctenomys* sp. (the "tuco-tuco"), that builds extensive tunnels in the coastal eolian dunes at the South of Brazil.

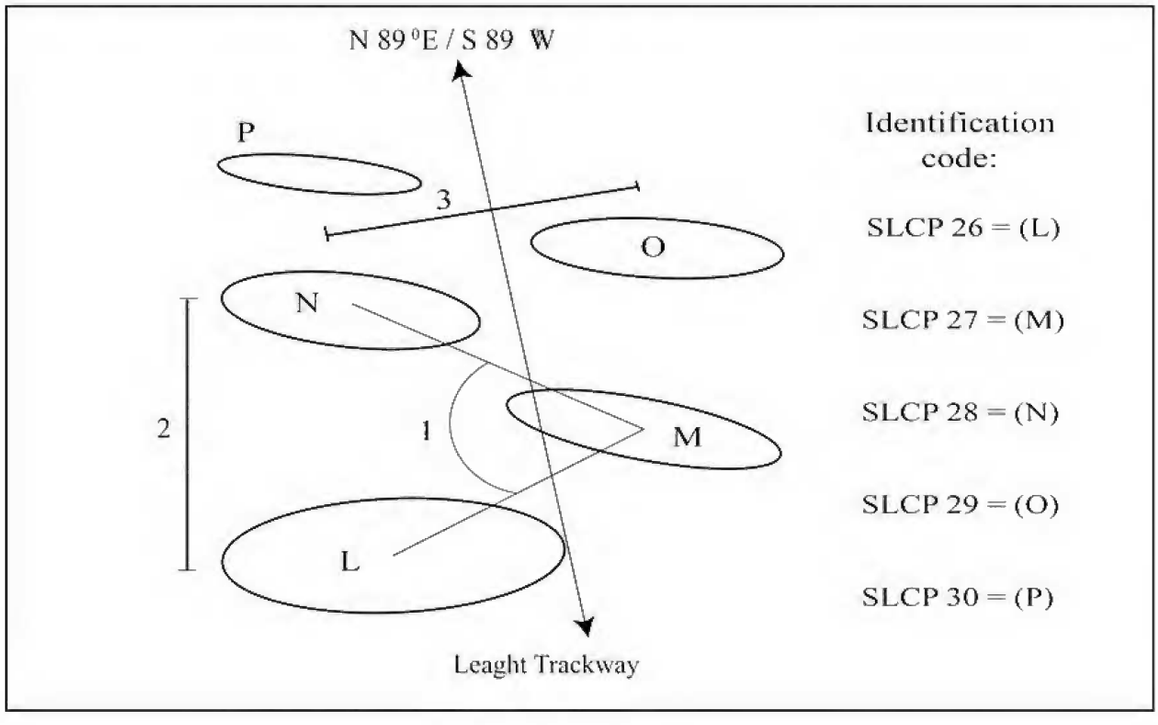
Fig.6- Sauropod footprint in section, gradually come out of the wall.

A third fossiliferous outcrop (RSCT) is also located in a dirt road, westward from Rosário do Sul city, near the Cerro Torneado hill. The basal layers of this outcrop are composed of palaeodunes with palaeocurrents directed to North, while its upper portion reveals a sequence of eolian sand sheets that are totally bioturbated by superimposed trackways. Footprints and trackways can be viewed both in section and on the surface. It was possible to identify at least three trackways of bipedal animals, two of theropods and one of an ornithopod.



Identification Code: SLCP 11 = (A) SLCP 12 = (B) SLCP 13 = (C)
SLCP 14 = (D) SLCP 15 = (E) SLCP 16 = (F) SLCP 17 = (G)
SLCP 18 = (H) SLCP 19 = (I) SLCP 20 = (J) SLCP 21 = (K)

Fig.7- North sauropod trackway with respective measurements (LEONARDI *et al.*, 1987).



1 - Pace angulation: 107°
2 - Stride: 1,50m
3 - width of pace: 0.60m

Fig.8- South sauropod trackway from the outcrop SLCP with respective measurements (Leonardi *et al.*, 1987).

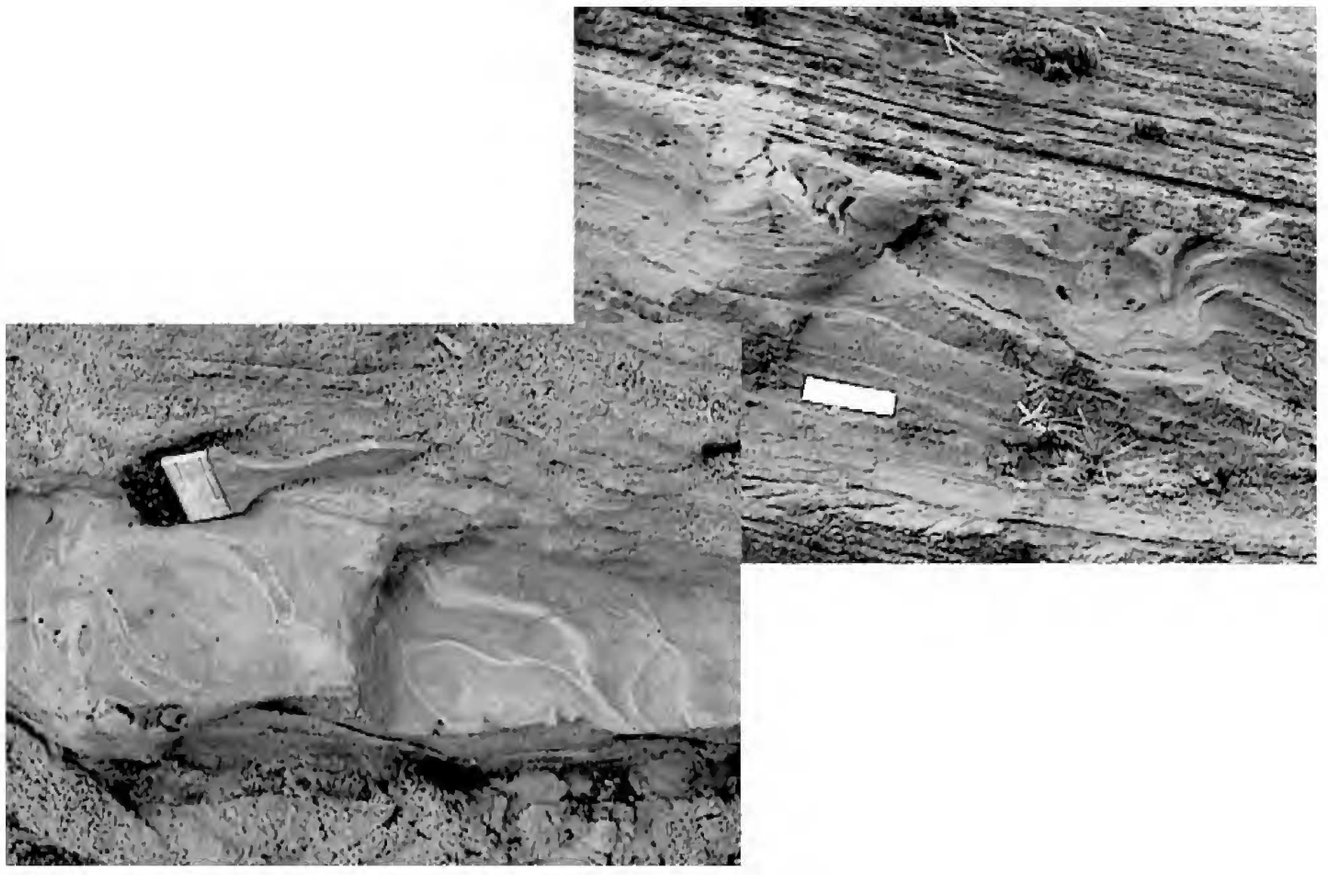


Fig.9- Theropod footprints in section and in surface view.

Fig.10- Burrow with 2.80m of length and 20cm of width.

Theropod footprints can be distinguished from those of ornithopods by the shape of the heel, the larger length of the fingers and for the presence of marks of claws (Fig.12), but they don't allow a distinction between a coelurosaur or carnosaur pattern.

The first RSCT trackway, made by a theropod, is directed to southwest and has footprints 35cm in length and 26cm in width. The step angle is 148° and the length of the stride is 110cm (Fig.13). This theropod would have been about 3m height. The second trackway, attributed to a theropod too, is directed to the northeast and has footprints 22cm in length and 15cm in width (Fig.14). The length of the stride is 75cm and the step angle is 175°. The only trackway from the RSCT outcrop that could surely be attributed to an ornithopod (Fig.15) is directed to North, its step angle is 155° and the length of the stride is 120cm. All the footprints are poorly preserved and don't stand out from the surface. Only the outlines of the deformations produced in the sand by the steps can be distinguished. At the margins of the road, about 50cm of this eolian sand sheet sequence can be observed in section showing that almost all its internal layers are completely bioturbated by superimposed footprints. It suggests a frequent transit of animals in that region at the time of the deposition of the layers.

A fourth tracksite was found near the Touro Passo stream, in Rosário do Sul Town (RSTP). This outcrop is represented by a succession of eolian and lacustrine sediments. In the eolian dunes some invertebrate traces were found, but the preservation was not good enough to permit a classification. However, in the eolian sand sheets, in section and surface, rounded footprints are clearly visible. The diameter of the footprints is about 45cm and the distance between them around 1m, while the depth varies between 15cm and 30cm. These footprints are very similar to those described at the first tracksite, which also leads us to classify them as middle-sized sauropods.

Finally, in the west of Rosário do Sul city, near to the Granja Santa Vitória (RSGV), another tracksite reveals a layer of eolian sand sheets, about 30cm thick, totally disturbed by dinosaur footprints. Some of them can be seen in section and others on the surface. One of the footprints is 25cm long and 23cm wide and shows well defined outlines. The heel has a "U" shape and no claw trace in the toes, which leads us to attribute it to a bipedal ornithopod about 2m in height.

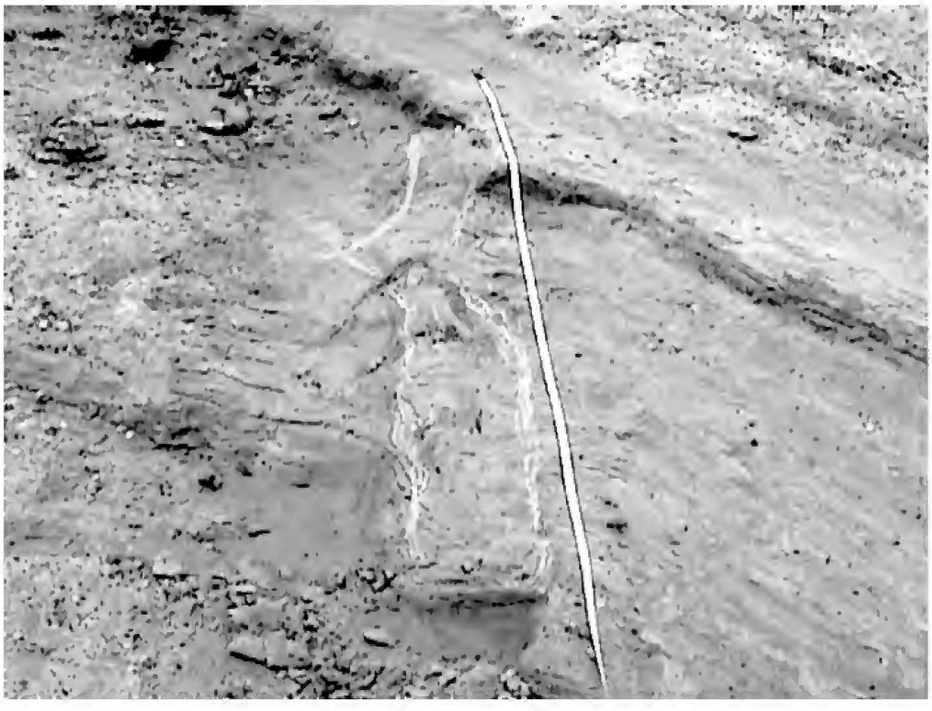


Fig.11- Bifurcated burrow from outcrop RSSJ.

Fig.12- Theropod footprint from outcrop RSCT.

DISCUSSION

Regarding to the dinosaur footprints, based on track morphology, we inferred sauropods (or, less probably, prosauropods), theropods, and ornithopods. We recognize that poor preservation makes trackmaker identification difficult. So our inferences presented below, are tentative. These three kinds of footprints don't occur together in any of the outcrops. In the outcrop RSSJ there are only theropod footprints, while in SLCP only sauropod footprints are present. In RSCT outcrop we infer associated theropods and ornithopods, but no sauropods. Some of the theropod footprints in RSSJ and RSCT have similar sizes and shapes, but the poor preservation does not allow us to infer a direct correlation.

From this we get that there is no direct evidence of an association between the sauropods (prosauropods?) and the other groups, but we assume such a temporal coexistence based on the modest thickness of the Guará Formation as a whole (about 200m) and its internal homogeneity, specially regarding to the eolian facies, where the footprints occur. But even accepting the coexistence of these three groups of dinosaurs, it does not provide any precise chronostratigraphic information. Such an association could as easily be Upper Triassic as Cretaceous. However, the palaeocurrents measured in the fluvial layers of the Guará Formation point to S/SW, while the whole Triassic package from Rio Grande do Sul State shows paleocurrents directed to N/NE.

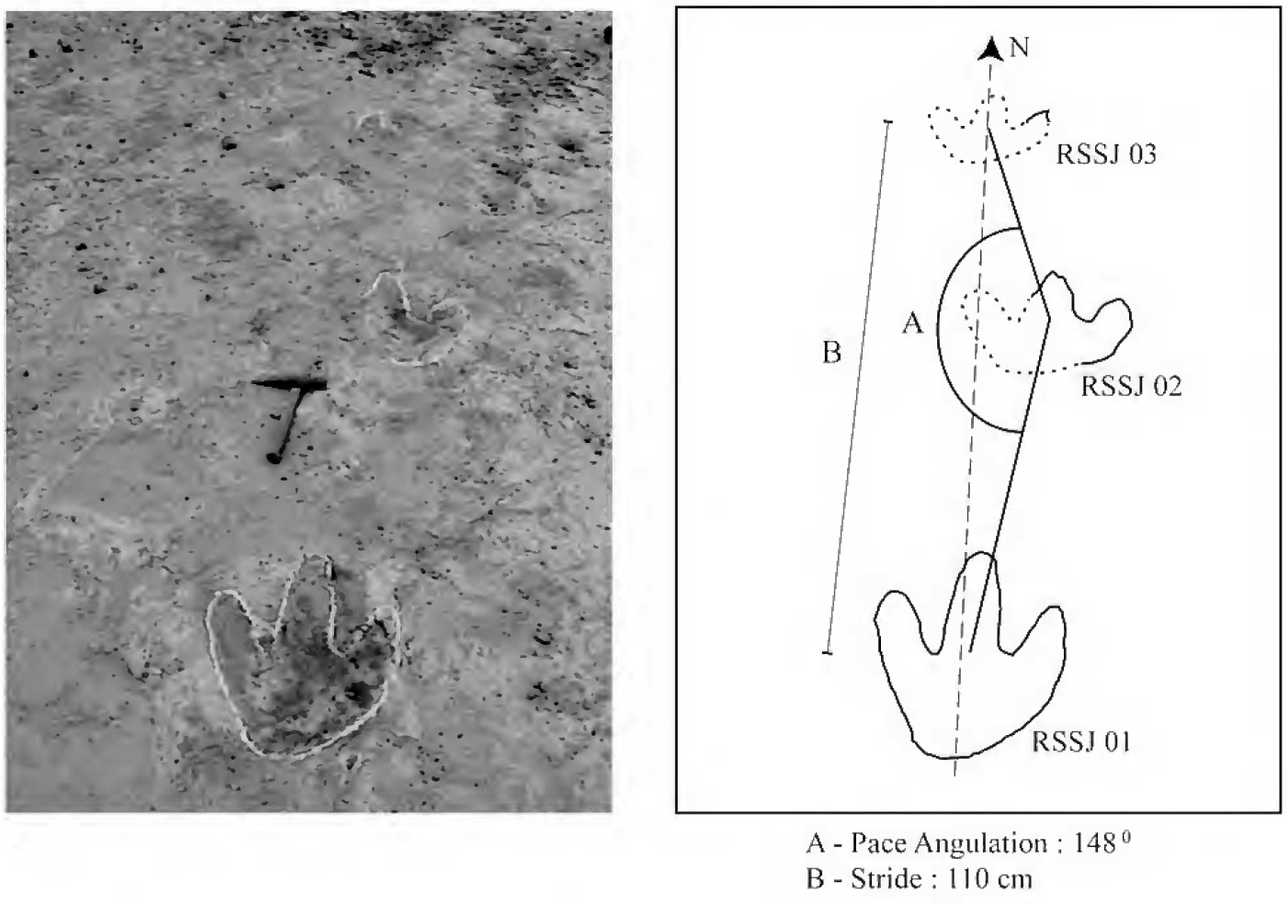


Fig.13- Theropod trackway with respective measurements (Leonardi *et al.*, 1987).

It is, therefore, not possible to infer such a structural change in the basin occurring during the end of the Triassic. So, the Guará Formation could not have been deposited at that time.

On the other hand, the overlaying Botucatu Formation has a minimum age of 132m.y. (Scherer, 2000). It decreases (but does not exclude) the possibility of a Lower Cretaceous age for the Guará Formation.

There is no Late Jurassic record of dinosaur's footprints for South America, in order to compare it with that from Guará Formation. The shape and size of some theropod footprints from Guará Formation are roughly similar to those found in the Cretaceous of Argentina (Rio Limay Formation, Albian to Cenomanian) and Brazil (Sousa Formation, Lower Cretaceous), but it is not conclusive.

The other fossils found in the Guará Formation, including the burrows of vertebrates and invertebrates, also do not furnish any usefull chronostratigraphic information.

So, the assumption of a Late Jurassic age for the Guará Formation is still tied to the lithostratigraphic correlation with the Tacuarembó Formation (Santa-Ana & Veroslavsky, 2003; Scherer & Lavina, 2005) from Uruguay. Concerning the biostratigraphic criteria, still no shared fossils are known for these units.

CONCLUSIONS

During the time of the Guará Formation sedimentation, in the west of Rio Grande do Sul State, a diversity of dinosaurs coexisted, probably including sauropods, theropods,and ornithopods, whose footprints and trackways were registered in the eolian facies of the Guará Formation.

Fig.14- Theropod trackway with 22cm of length and 15cm of width.

The depositional environment associated with the Guará Formation was relatively dry as evidenced by the eolian sedimentation, mainly dunes and eolian sand sheets.

Footprints and trackways are present only in the eolian facies including dunes and sand sheets. This reduces the anatomic details of tracks that can be preserved.

The ichnofossils does not allow us to establish a precise age for the Guará Formation. An association of theropods, ornithopods, and sauropods dinosaurs could be either Triassic as Cretaceous.

The main direction of the palaeocurrents measured in the fluvial layers of the Guará Formation (to South) is totally different from that one from the Triassic package (to N-NE) from Rio Grande do Sul State. It is, therefore, not possible to imagine such a structural change in the basin occurring during the end of the Triassic. So, the Guará Formation could not have been deposited at that time.

The Late Jurassic age here proposed as most probable for the Guará Formation is also supported by the lithostratigraphic correlation with the Tacuarembó Formation from Uruguay, although no

common taxa have yet been found in these two units. This study may encourage more detailed studies in the Guará Formation that can provide well-preserved vertebrate ichnofossils to improve the knowledge of those tracks.

Fig.15- Ornithopod trackway with footprints about 43cm of length and 34cm of width.

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